

Beam-generated plasmas for processing applications*

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The use of moderate energy electron beams (e-beams) to generate plasma can provide greater control and larger area than existing techniques for processing applications. Kilovolt energy electrons have the ability to efficiently ionize low pressure neutral gas nearly independent of composition. This results in a low-temperature, high-density plasma of nearly controllable composition generated in the beam channel. By confining the electron beam magnetically the plasma generation region can be designated independent of surrounding structures. Particle fluxes to surfaces can then be controlled by the beam and gas parameters, system geometry, and the externally applied rf bias. The Large Area Plasma Processing System (LAPPS) utilizes a 1–5 kV, 2–10 mA/cm² sheet beam of electrons to generate a 10¹¹–10¹² cm⁻³ density, 1 eV electron temperature plasma. Plasma sheets of up to 60×60 cm² area have been generated in a variety of molecular and atomic gases using both pulsed and cw e-beam sources. The theoretical basis for the plasma production and decay is presented along with experiments measuring the plasma density, temperature, and potential. Particle fluxes to nearby surfaces are measured along with the effects of radio frequency biasing. The LAPPS source is found to generate large-area plasmas suitable for materials processing. © 2001 American Institute of Physics. [DOI: 10.1063/1.1345506]

I. INTRODUCTION

Electron beams can generate processing plasmas with greater process control and larger area than present plasma generation techniques such as capacitive or inductive discharges,¹ electron cyclotron resonance (ECR),² surface wave, or helicon³ reactors. All of these techniques use electric fields to heat free electrons to ionize the background gas. This results in a relatively hot plasma ($T_e \sim 2\text{--}5$ eV) whose equilibrium depends on the working gas, the electric field source, and the chamber geometry. Moreover, the ionization is generally nonlocal resulting in nonuniformities in plasma density, temperature, and processing. The beam technique avoids this by using an externally generated flux (2–10 mA/cm², 1–4 kV) of electrons to ionize the gas. Such beams have been shown to generate 60×60 cm² sheets of high-density (10¹² cm⁻³), cold (≤ 1 eV) plasma.^{4,5} The ionization is independent of the chamber geometry and gas composition. The plasma production can be controlled by confining the beam electrons with magnetic fields, such as in the Naval Research Laboratory's (NRL's) Large Area Plasma Processing System (LAPPS),⁶ or by allowing them to expand to fill the region above a surface.^{7,8} In this way square-meter plasma layers can be generated for processing applications. This article outlines the theory of beam-generated plasmas, experimental results from large area sheet plasmas, and initial processing results for both pulsed and cw beam-produced plasmas.

II. BEAM-PRODUCED PLASMAS

LAPPS provides several important advantages over conventional plasma sources that rely on heating the plasma electrons. These advantages include efficient ionization and dissociation; independent control of the ion and radical fluxes; high uniformity over large area; wide range in gas type and density; and low electron temperature. In this section we briefly discuss the basis for these attributes.

Energetic electrons create one electron–ion pair for every 30 eV or so of energy deposited in the background gas. The ionization efficiency thus approaches 50% for ionization energies ~ 15 eV, with the excess energy going mainly into dissociation and inelastic collisions. By contrast, the ionization efficiency of conventional plasma sources under similar conditions is only $\sim 1\%$. Most of this additional energy goes into low-level excitation, metastables, and ultimately heat.

The plasma density n depends on the beam parameters, gas type, and system geometry.⁹ The balance between the loss and production rates is described by

$$\beta n^2 - D_a \nabla^2 n = \frac{j_b}{e} N \sigma_e(\epsilon_b). \quad (1)$$

Here β is the electron–ion recombination coefficient, D_a is the ambipolar diffusion coefficient, j_b is the beam current density, N is the gas density, and $\sigma_e(\epsilon_b)$ is the effective beam ionization cross section including the cascade contribution. The ionization cross section $\sigma_e(\epsilon_b)$ is $\sim 10^{-16}$ cm² for a beam energy $\epsilon_b = 2$ keV in gases like oxygen and argon. The dissociative recombination coefficient β is very small in atomic gases but is $\sim 10^{-7}$ cm³/sec in molecular gases. The ambipolar diffusion coefficient depends on the

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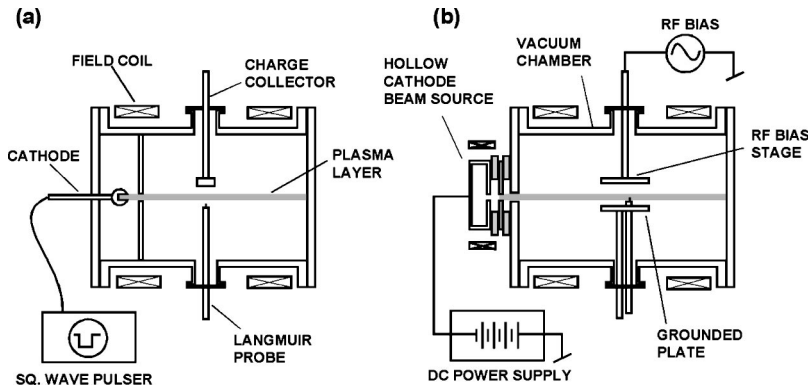


FIG. 1. Schematic of LAPPS experimental chambers including pulsed (a) and cw (b) e-beam sources.

magnetic field but can be approximated in LAPPS by $D_a \sim 10^3/P \text{ cm}^2/\text{sec}$, where P is the gas pressure in torr.

Using Eq. (1), one can show⁹ that recombination limits the flux of molecular ions reaching a surface outside the beam to

$$F_{im}(\Delta x) = -D_a \nabla n \leq 35 \frac{D_a^2}{\beta \Delta x^3}, \quad (2)$$

where Δx is the distance from the beam edge to the surface. Dissociative recombination converts each molecular ion into two free radicals, and thus the flux of radicals grows according to

$$F_r(\Delta x) = \frac{I_b N(\sigma_e + \sigma_d)}{e} - 2F_{im}(\Delta x). \quad (3)$$

Here σ_d is the cross section for beam dissociation, and I_b equals j_b integrated over the beam width w_b . Equal and opposite fluxes flow from the both sides of the beam.

Since $\beta \approx 0$ in atomic gases, the radical flux is zero while the ion flux is constant outside the beam,

$$F_{ia} = \frac{I_b N \sigma_e}{2e}. \quad (4)$$

According to Eqs. (2)–(4), the ion and radical fluxes can therefore be adjusted independently by varying the gas composition and standoff distance Δx . Such adjustment is generally not possible in conventional sources. Using the parameters cited previously, a beam of width $w_b = 1 \text{ cm}$ and current density $j_b = 10 \text{ mA/cm}^2$ can produce ion and radical fluxes above $10^{16} \text{ cm}^{-2} \text{ sec}^{-1}$ at gas pressures of 50 mtorr or more ($N \geq 1.6 \times 10^{15} \text{ cm}^{-3}$). Raising the gas density or beam current increases the fluxes. Note that the fluxes produced are uniform to the extent that I_b and ε_b are uniform. In general, current continuity maintains I_b , but collisional energy loss causes ε_b to vary. This variation can be reduced by raising ε_b , but at the expense of system efficiency.

Considering recombination as the main ion loss mechanism, the on-axis plasma density satisfies

$$n_o = \sqrt{\frac{j_b N \sigma_e}{e \beta}}. \quad (5)$$

This yields $n_o \sim 10^{12} \text{ cm}^{-3}$ for the parameters cited above. In atomic gases the density is higher yet, and for $\Delta x \gg w_b$,

$$n_o \approx \frac{I_b N \sigma_e}{e D_a} \Delta x. \quad (6)$$

For example, if the walls lie at $\Delta x \geq 20 \text{ cm}$ from the beam, densities as high as 10^{13} cm^{-3} are possible in argon for the parameters given.

In conventional sources, electromagnetic fields heat the electrons until electron thermal ionization balances the plasma loss rate. In LAPPS, however, beam ionization balances the loss rate, and there are no fields to heat the electrons. As a result $T_e \sim 0.5 \text{ eV}$ in molecular gases and somewhat higher in atomic gases like argon. However, in atomic gases, contamination levels as low as 0.1% can keep $T_e \leq 1.5 \text{ eV}$.

III. EXPERIMENTAL SETUP

A. Experimental apparatus

1. Vacuum chambers

Two aluminum (50 cm diameter, 65 cm long) and one acrylic (38 cm diameter, 50 cm long) chambers were used (see Fig. 1). High purity argon, nitrogen, or oxygen was introduced through a needle valve or mass flow controller, and experimental pressures (30–100 mtorr) were monitored with Pirani or Convectron[®] vacuum gauges. A pair of Helmholtz field coils was wound around each aluminum chamber or on coil forms outside the acrylic chamber. The coils were driven with a dc power supply generating 150–250 G along the axis of the chamber. The magnetic field varied less than 2% along the chamber axis and less than 10% 15 cm off axis.

2. Pulsed e-beam source

Most of the experiments were performed using a pulsed cathode [see Fig. 1(a)] that generated a 1 cm thick by 15–30 cm wide, 1–3 kV, 2–5 mA/cm² electron beam. The cathode consisted of a rectangular channel (1 cm wide, 1.5 cm deep, 15–30 cm long) surrounded by a Teflon insulator and a grounded outer shield. The cathode was embedded in a 100–250 G magnetic field which confines the beam electrons. An insulated gate bipolar transistor (IGBT) switched pulse generator was used to drive the beam.¹⁰ Sheet beams up to 60 cm wide and 8 kV have been produced using this type of cathode.¹¹ The pulsed beam was passed through a 1 cm wide stainless steel aperture located 5 cm downstream. This aper-

ture served as the grounded anode for the cathode and defined the beam size as it entered the experimental chamber. The beam terminated on a grounded metal beam dump at the far side of the chamber.

3. CW e-beam source

Most processing operations require seconds of exposure to plasma. A new e-beam source that operated in the 30–100 mtorr background pressure used for LAPPS was developed to investigate cw plasma effects. This source consisted of a $1 \times 30 \text{ cm}^2$ plasma cathode which could be electrically floated at high voltage. A 30 cm wide, 2–5 mA/cm², 1–5 kV electron beam could be extracted through a 1 cm wide aperture from this cathode.¹² Figure 1(b) shows a schematic of the source which could be operated continuously or modulated.

B. Diagnostics

1. Langmuir probes

Several different versions of Langmuir probes were used to diagnose the LAPPS plasma.¹³ The probes were made with a short piece of thoriated tungsten wire extending beyond an alumina insulator. For some of the experiments a current-carrying nichrome wire was wound around the alumina tube to heat the probe to $\sim 500^\circ\text{C}$ to reduce surface contaminants. The current collected by the wire was measured as a function of the probe bias voltage. Current-voltage (I-V) characteristic curves were generated by using either a programmable saw-toothed power supply or an isolated variable voltage battery supply and appropriate sensors.

2. Emissive probe

An emissive probe was used to measure the plasma potential.¹⁴ The probe consisted of a loop of the 10-mil tungsten wire, heated to incandescence by a floating current supply, and biased relative to ground. Emission from the filament determined the plasma potential to within a fraction of a volt.

3. Ion flux diagnostics

A cylindrical, retarding-field gridded energy analyzer was used to measure ion flux.¹⁵ A 6.3 mm aperture in a grounded electrode contained a 500 line per inch mesh biased at -9 V followed by a similar screen with a variable bias and a collection electrode set at -300 V . Ions with sufficient energy to pass the variable bias screen were collected by the electrode. The collected current signal was differentiated to give a signal proportional to the ion energy distribution.

4. Mass spectrometer

Ion flux and energy distributions were measured with a Hiden EQP 300 Plasma Probe that consists of an electrostatic ion-energy analyzer (ESA) in series with a quadrupole mass spectrometer (QMS). The probe was inserted perpendicular to the plasma sheet at varying distances from the beam edge. Ions incident to the electrode entered the differentially

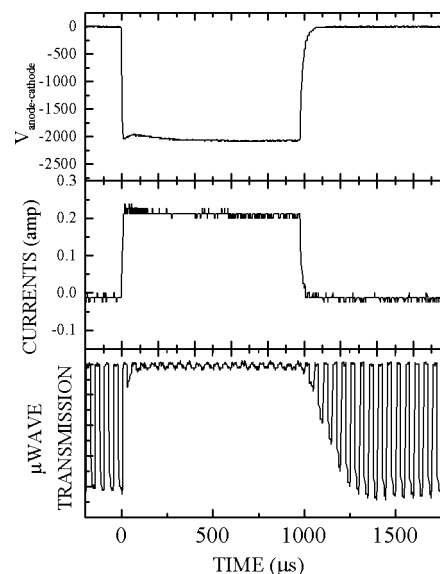


FIG. 2. Typical voltage and current data from pulsed e-beam source along with 1.5 GHz microwave transmission signal.

pumped EQP through a $100 \mu\text{m}$ diameter aperture located in the center of the electrode. Alternatively, the probe could function as a residual gas analyzer (RGA). In this mode, neutrals diffusing through the orifice were ionized via an internal electron source and then analyzed.¹⁶ Time-resolved measurements were achieved by gating the detector output.

IV. EXPERIMENTAL MEASUREMENTS AND DISCUSSION

The experiments were designed to establish the basic concept of using sheet e-beams to generate processing plasmas and to test some of the theoretical predictions. Experiments were performed in nitrogen, oxygen, and argon using both pulsed and cw e-beam cathodes.

A. Pulsed e-beam parameters

Figure 2 shows time-resolved measurements from the pulsed electron beam. These data come from the acrylic experimental chamber filled with 75 mtorr nitrogen in a 150 G magnetic field. The 2 kV voltage pulse drove $\sim 200 \text{ mA}$ of cathode current from the 22 cm wide cathode. Approximately half of the current was from high energy electrons, giving a beam current density of $\sim 5 \text{ mA/cm}^2$. Equation (5) predicts $n \sim 8.5 \times 10^{10} \text{ cm}^{-3}$ for these conditions. The bottom trace of Fig. 2 shows the transmission of a 1.5 GHz microwave beam through the plasma. The microwave system consisted of transmitting and receiving horns on either side of the acrylic chamber aligned perpendicular to the planar plasma sheet. Cutoff of the transmitted signal suggests that the plasma density exceeds $5 \times 10^{10} \text{ cm}^{-3}$, agreeing well with prediction.

B. Langmuir probe measurements

1. Characteristic I-V curves

Figure 3 shows typical time-resolved probe currents at the center of a nitrogen discharge with a 2 kV, 800 μsec

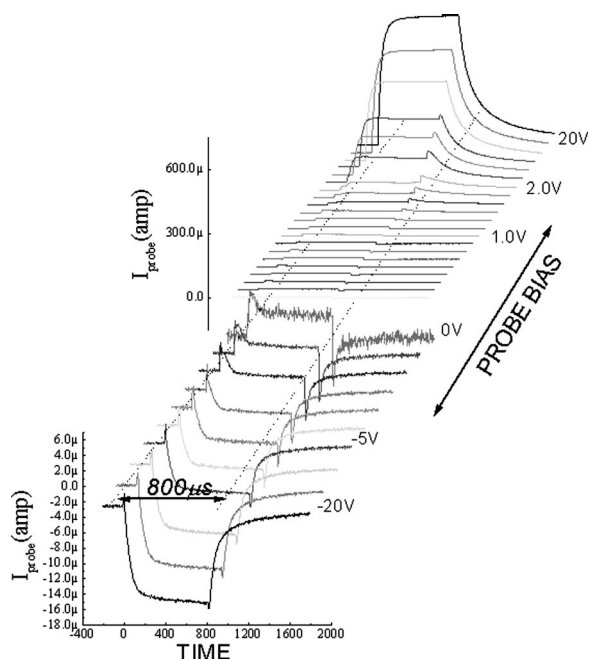


FIG. 3. Raw data from a biased Langmuir probe near the center of a nitrogen plasma layer. Probe bias varied from 20 to -20 V. Note probe current scale differences.

pulse.¹⁴ The heated Langmuir probe was used and time-resolved probe currents were recorded on a digital oscilloscope. The individual traces show a few μsec risetime signal, a flat top, and a decay lasting up to several hundred μs . The signals mimic the beam current with the exception of the tail after the pulse. For large negative bias the probe measured the ion saturation current, which is directly related to the local plasma density. The measurements indicate a plasma density of $n_o \approx 5 \times 10^{11} \text{ cm}^{-3}$ which agrees with both the microwave cutoff and theoretical predictions.

Figure 4 shows typical I-V curves generated from data similar to Fig. 3 with 85 mtorr argon in a 120 G magnetic field. In this case a 7.5 GHz microwave beam was cut off by the plasma indicating $n_o > 7 \times 10^{11} \text{ cm}^{-3}$. The I-V characteristic changes little during the pulse but changes rapidly in the

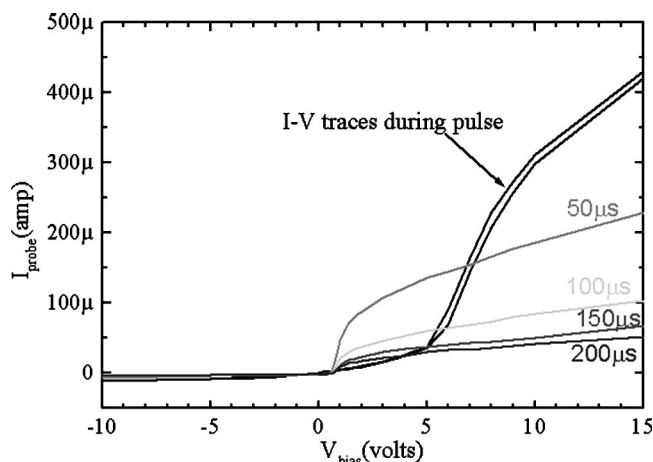


FIG. 4. Typical I-V characteristic for a Langmuir probe in an argon plasma layer.

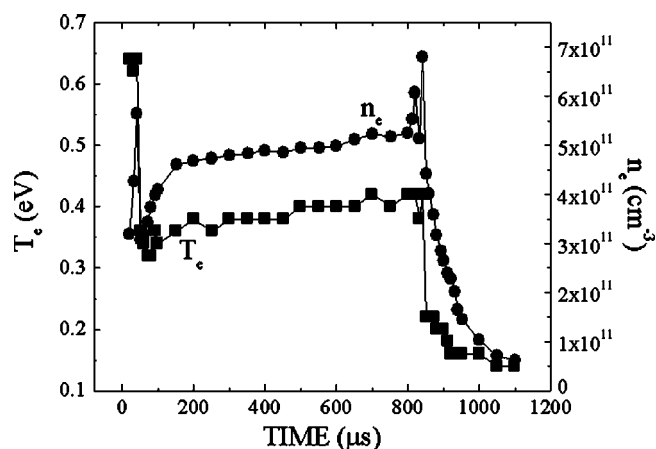


FIG. 5. Electron temperature and plasma density for a nitrogen plasma as computed using a two-temperature Maxwellian fit to I-V curves.

afterglow, after the pulse. The start of the electron collection portion of the curve shifts negative and the electron collection current drops rapidly when the beam is turned off. Equation (6) predicts a plasma density $n_o \approx 10^{12} \text{ cm}^{-3}$ during the pulse for these beam parameters in argon. This agrees with the microwave measurements. The plasma potential is the voltage at which the slope of the I-V curve changes rapidly. During the pulse the plasma potential ranges from 4–8 V with some of the uncertainty caused by probe contamination. When the beam is turned off, the plasma potential falls by 3–5 V, which is consistent with a rapid decay of the electron temperature. Likewise the electron saturation current measured at high positive bias drops rapidly after the pulse. This indicates that the plasma density decays rapidly.

2. Time-resolved plasma density and temperature

The characteristic I-V curves were analyzed using a two-temperature, Maxwellian fitting routine.¹⁷ This routine assumes a $V^{1/2}$ scaling in the ion saturation region and a two-temperature Maxwellian [$\sim \exp(-V/T_e)$] at higher voltages. Variables of the fit are automatically adjusted to minimize the discrepancy between the fit and the data.

Figure 5 shows the results for the nitrogen plasma (75 mtorr, 150 G, 800 μsec pulse). The plasma density in this case reaches $n_o \approx 5 \times 10^{11} \text{ cm}^{-3}$ after $\sim 150 \mu\text{sec}$ from the beginning of the pulse. The two-temperature fits yielded a cold, dense component and a second component with 30% of the density but several times the temperature. The density grows slowly over the 800 μsec pulse before decaying in $\sim 100 \mu\text{sec}$ after the pulse. The electron temperature has a similar profile, reaching 0.35 eV early on and growing slowly to 0.4 eV during the pulse. The temperature decays faster than the density after the pulse. Similar data for an argon plasma give $n \approx 3 \times 10^{11} \text{ cm}^{-3}$ and $T_e \approx 1.2 \text{ eV}$ during the pulse. These data illustrate that beam-generated plasmas can produce high plasma density and low electron temperatures.

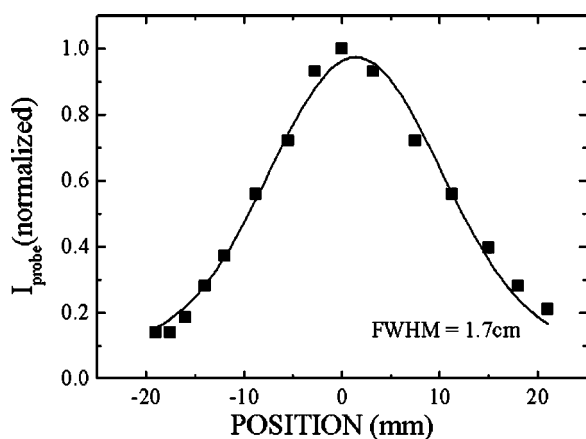


FIG. 6. Ion saturation current profile for a Langmuir probe moved through a nitrogen plasma sheet.

3. Plasma profile measurements

Figure 6 shows the Langmuir probe ion saturation current as a function of distance from the center of the nitrogen plasma sheet. The normalized probe data show a peaked distribution with ~ 17 mm full width at half maximum (FWHM). The beam is defined by the 1 cm wide aperture where it enters the experimental region. The gyroradius of a 2 kV electron in a 150 G magnetic field is $r_g \approx 7$ mm. Assuming the beam has a range of transverse energies up to the full 2 kV energy, the measured width is reasonable. Measurements indicate the plasma density in this nonoptimized case is constant to within 5% along the beam axis.

C. Emissive probe measurements

Figure 7 shows the I-V characteristic of an emissive probe in a nitrogen plasma.¹⁶ The data were taken near the center of the layer and during a 30 μ sec window in the middle of the 1 msec pulse. The probe emits electrons based on its temperature and the local plasma potential. The different curves show the effect of increasing the temperature by changing the current through the probe. The point where the probe starts to emit, $V \approx 0.8$ V, provides an accurate measure of the local plasma potential. The plasma potential is usually a factor of ~ 5 higher than the plasma electron temperature.¹⁸

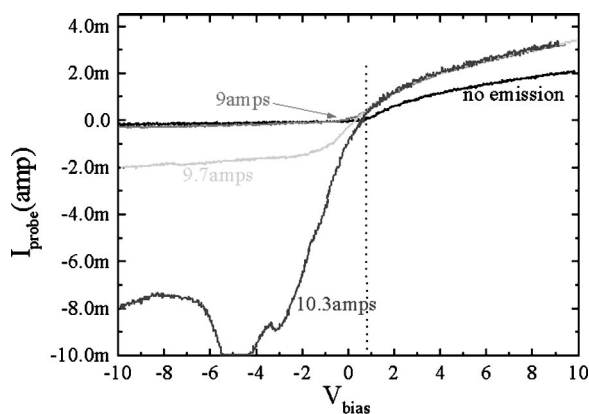


FIG. 7. Emissive probe characteristic for a nitrogen plasma. Probe heated by driving 9–10.3 A through the tungsten wire.

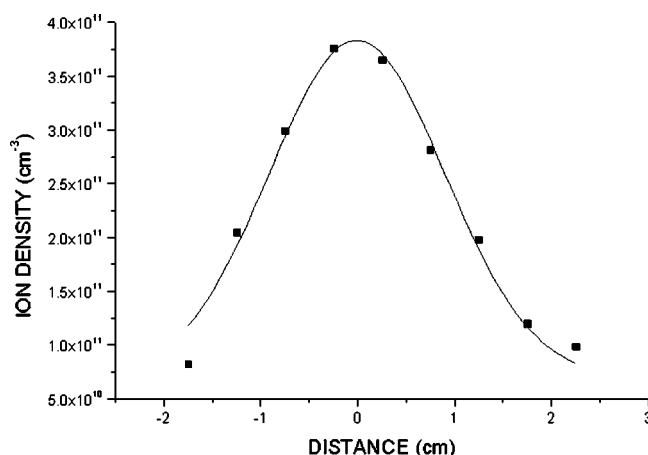


FIG. 8. Ion density profile from an argon plasma sheet with the cw beam source.

Figure 5 shows the electron temperature for a similar nitrogen plasma to be ≈ 0.35 eV, which is slightly higher than predicted by the emissive probe but still small. Emissive probe data taken in argon show a plasma potential of ≈ 1.7 V, or nearly twice the nitrogen level.

D. CW beam measurements

In general the results using the cw beam source were similar to the pulsed source. Figure 8 shows a transverse ion density profile for an argon plasma generated by a 1 kV cw beam source. The beam current density was ~ 3 mA/cm² and was injected into a 50 mtorr argon background in 250 G magnetic field. The peak ion density was $n_i \approx 3.8 \times 10^{11}$ cm⁻³ and the distribution had a FWHM ≈ 27 mm. The peak density is similar to that measured in the pulsed case. The FWHM is slightly wider than in the nitrogen case shown in Fig. 6. This is not unexpected, due to the lower beam energy (1 kV vs 2 kV) and the use of argon rather than nitrogen. Argon is an atomic gas, and therefore n is primarily controlled by diffusion rather than recombination, making the profile wider.

E. Charge collector measurements

1. Mass spectrometer measurements

Figure 9 shows the energy distribution of argon ions (Ar^+) measured by the EQP at three different distances from the beam edge in the aluminum chamber. The ion flux was integrated from 0.2 to 1.0 msec during a 1 msec pulse. The sampling orifice was grounded in this case and the detector resolution (FWHM) set to its minimum value of 0.3 eV. The normalized distributions show a maximum energy of ~ 4.5 eV with a peak at ~ 3.5 eV at 1 cm from the beam and a FWHM of ~ 1 eV. The distribution appears to shift to lower energy as the distance to the probe increases. The ion energy should correlate with the plasma potential with an error bar of ± 1.3 eV due to an offset of the absolute particle energy due to charging of the surfaces in the energy analyzer. The shift of the distribution toward lower energy with increasing path length illustrates ion energy loss to the background gas. Similar data taken with an oxygen plasma showed a peak

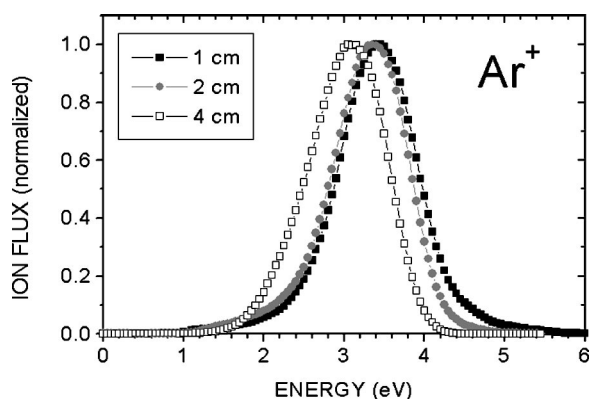


FIG. 9. Energy distribution of Ar^+ ions at three different distances from the beam edge.

particle energy of ≈ 1.2 eV at 1 cm, indicating a lower plasma potential for the oxygen case. A similar shift toward lower energy with distance was observed. The absolute intensity of the Ar^+ signal also decreased with distance. At the same time the EQP measured an increase in the ArH^+ and H_2O^+ flux with distance. Since ArH^+ and H_2O^+ ions are produced by charge exchange of H_2O with Ar^+ , measurements of the background gas with the EQP in RGA mode were made. Results showed that there was as much as 0.1% H_2O in the chamber which was sufficient, owing to the high cross sections for these reactions, to account for the loss of Ar^+ . By heating the chamber and improving the base pressure, the water concentration was lowered by a factor of 20. This decreased the loss of Ar^+ with distance significantly.

2. Biased charge-collector measurements

A second measurement of the ion flux was made using the gridded ion flux probe. This measurement was simpler than using the EQP but could not discriminate between ion species. Figure 10 shows preliminary data for the ion energy distribution for oxygen and argon plasmas with the probe

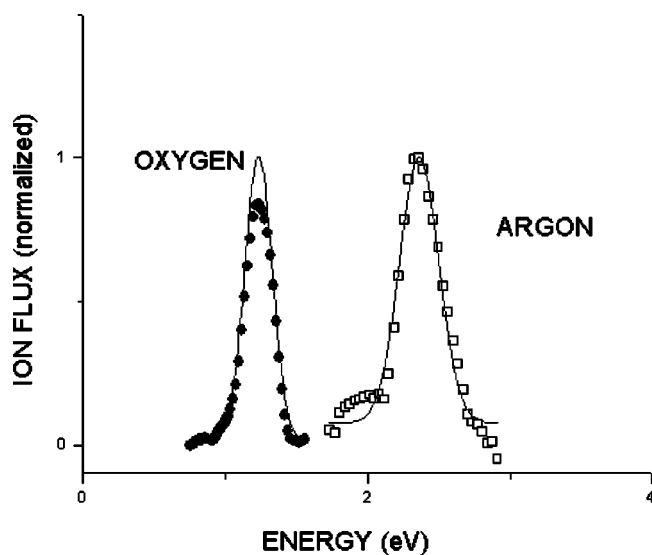


FIG. 10. Charge collector signals as a function of bias voltage for oxygen (solid) and argon (squares) plasma sheets.

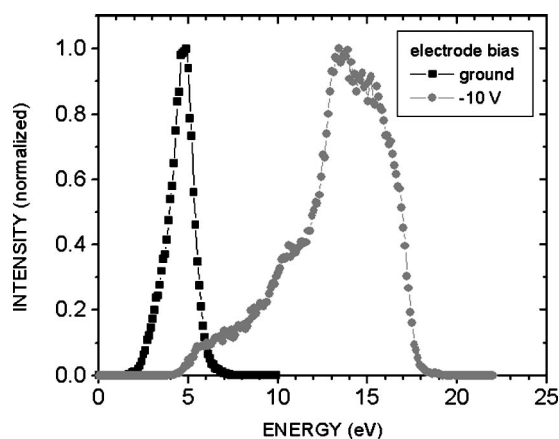


FIG. 11. Intensity of Ar^+ flux as a function of energy for an argon plasma. The EQP was mounted inside the rf-biased electrode located 2 cm from the edge of the beam. The electrode was either grounded or biased at -10 V with the rf.

located 1.5 cm from the edge of the beam. The data were taken near the center of the 1 msec pulse. The probe current was measured as a function of the bias voltage. Experiments were done with similar beams in 30 mtorr of argon and oxygen in a 150 G magnetic field. The oxygen plasma showed a peak energy of ~ 1.4 eV while the argon plasma showed a peak at ~ 2.8 eV. The measured peak energies were slightly higher than the plasma potentials measured with the emissive probe but had similar ratios.

F. RF bias effects

Figure 11 shows results of applying rf bias (11 V peak to peak voltage, 13.56 MHz) on an isolated stage close to an argon plasma sheet. The electrode was mounted on the end of the EQP and the rf bias was adjusted to give a dc bias voltage on the stage of -10 V. Ions entering the aperture were mass and energy analyzed with an energy acceptance window of 1 V. The figure shows the Ar^+ energy spectrum normalized to its peak for the electrode grounded and with the rf bias turned on. The shift in ion energy with the rf bias is apparent. Ions entering the EQP gain not only the plasma potential, which is ~ 5 V as seen in the grounded case, but the ~ 10 V dc component of the rf bias. The spread in ion energies is attributed to finite sheath transit time effects and scattering with the background gas. This illustrates that LAPPS is compatible with rf bias and that one could control the ion energy on a processing surface with rf.

V. DISCUSSION

This article contains a simple theoretical treatment of LAPPS and initial experimental data. In general, the experiments agree with theory. Thin (~ 2 cm FWHM), large area (30×45 cm²), high-density ($n \sim 10^{11}$ – 10^{12} cm⁻³), low-temperature ($T_e \leq 0.5$ – 1.0 eV) plasma sheets were produced using both pulsed and cw electron beams in molecular and atomic gases. The plasma density and ion fluxes fell with distance from the beam edge while the plasma density in the afterglow decayed and cooled rapidly. The layers were uniform and stable both in time and space. The plasma decayed

by diffusion to the surrounding region and/or by recombination with itself or background gas contaminants. Plasma potentials were $\sim 1\text{--}4$ V, in agreement with measurements of the ion energies exiting the plasma. Applying rf to an electrode near the plasma did not change the plasma production and was able to adjust the ion energy. Further experimental work is in progress to provide detailed measurements of the ion and radical fluxes, electron and ion temperatures, effects of rf, effects of gas composition, plasma uniformity, and processing of materials. Initial processing tests involving photoresist ashing have been performed in oxygen and show promise for future processing applications.

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